Primordial Comets

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Outline

- Testing consequences of the collisional cascade in the Primordial Disk as envisioned by the “standard model”:

- To what extent is water D/H values in the comet population homogenized by mixing?

- CO_2 with trapped HCN, CH4, Ar, N_2, and CO (Altwegg, Hansen): does such ice survive collisional heating?

Conclusions

- D/H homogenization appear efficient: <0.1% probability of finding a Hartley 2 (D/H=7.7 times solar) and a 67P (D/H=25.2 times solar) among 9 objects

- Collisional heating during disruption of D≥25km bodies likely leads to global CO_2 loss

- Comets like Rosetta's 67P are not likely to have been formed as part of a collisional cascade. They are most likely pristine

Background

- Rosetta rejuvenated a long-standing debate on whether comets have been processed in high-speed collisions

- Comets are not primordial bodies
  - Stern (1988, *Icarus* **73**, 499); Farinella & Davis (1996, *Science* **273**, 938); Stern & Weissman (2001, *Nature* **409**, 589); Weissman *et al.* (2004, *Comets II*); Morbidelli & Rickman (2015, *A&A* **583**, A43); Rickman *et al.* (2015, *A&A* **583**, A44); Jutzi *et al.* (2017, *A&A* **597**, A61); Jutzi & Benz (2017, *A&A* **597**, A62)

- Comets are primordial bodies
  - Weissman (1986, *Nature* **320**, 242); Weaver (2004, *Science* **304**, 1760); Brownlee *et al.* (2004, *Science* **304**, 1764); Belton *et al.* (2007, *Icarus* **187**, 332); Davidsson *et al.* (2016, *A&A* **592**, A63); Poulet *et al.* (2016, *MNRAS* **462**, S23); Basilevsky *et al.* (2017, *PSS* **140**, 80); Fulle & Blum (2017, *MNRAS* **469**, S39)

- This question is important: how does comet exploration contribute to Solar System science?
  - Do the *physical* properties of comets teach us about the initiation of planet formation?
  - Do the *physical* properties of comets teach us about disruption and gravitational re-accumulation?
  - The notion that the *chemical and mineralogical* properties date back to the Solar Nebula is much less controversial

“Standard model”

- There were ~ $2 \cdot 10^{11}$ comets with D>2.3km in the Primordial Disk (Brasser & Morbidelli (2013, *Icarus* **225**, 40):
  - About 117±50 visual JFCs with D>2.3km
  - Fractional decay rate $-(1.63 \pm 0.6) \cdot 10^{-10}$ yr^{-1} yield ~$2 \cdot 10^{9}$ comets in the Scattered Disk
  - The Scattered Disk is ~1% of the Primordial Disk, hence ~ $2 \cdot 10^{11}$ comets
- The differential size distribution index is in the range $-3.5 \lesssim q \lesssim -2.5$ (e.g., Morbidelli & Rickman 2015, *A&A* **583**, A43)
- The Primordial Disk is modestly dynamically excited: collision velocities typically 240-950 ms^{-1} and intrinsic collision probabilities significant among zone I (15-20AU), zone II (20-25AU), and zone III (25-30 AU)
- Nominal Primordial Disk lifetime: ~ 400 Myr (e.g., Morbidelli *et al.* 2012, *EPSL* **355-356**, 144)

Target / Projectile	I	II	III
I	1.85×10^{-20} 0.78 0.23	3.75×10^{-21} 0.74 0.24	1.00×10^{-24} 0.95 0.20
II	3.75×10^{-21} 0.74 0.24	8.95×10^{-21} 0.44 0.33	7.95×10^{-22} 0.38 0.37
III	1.00×10^{-24} 0.95 0.20	7.95×10^{-22} 0.38 0.37	7.32×10^{-21} 0.24 0.51

Image credit: Morbidelli & Rickman 2015, *A&A* **583**, A43

Deuterium

- Work done in collaboration with Dr. Sona Hosseini at JPL
- Motivation for the work: accretion of foreign material during cratering, shape changing, subcatastrophic, and catastrophic collisions
- Description of the numerical evolution model
- First results

Accumulation of foreign material

- Critical energies Q for various impact types from SPH and scaling laws
- Matching Q with kinetic energy of projectiles yield their radii

$$Q_{\mathrm{crit}} = aR^{3\mu}V^{2-3\mu}$$

Image credit: Jutzi & Benz (2017, *A&A* **597**, A62)

Scaling	μ	a
Q^*_{D}	0.42	4.00e-4
Q_{reshape} (average)	0.42	2.50e-6
Q_{sub} (0.4)	0.42	1.66e-5
Q_{sub} (0.7)	0.42	4.90e-5

- For any target in zone i: number of projectiles (N_{coll}) from zone j
- Total mass accumulated

$$N_{\mathrm{coll}} = P_{\mathrm{i}}\delta t \int_{\mathrm{r_{min}}}^{r_{\mathrm{max}}} (R_{\mathrm{t}} + r)^2 \, N_0 r^{-q} \, dr$$

$$M = \frac{4\pi\rho}{3} P_{\mathrm{i}}\delta t \int_{\mathrm{r_{min}}}^{r_{\mathrm{max}}} (R_{\mathrm{t}} + r)^2 \, N_0 r^{-q} r^3 \, dr$$

Cratering collisions

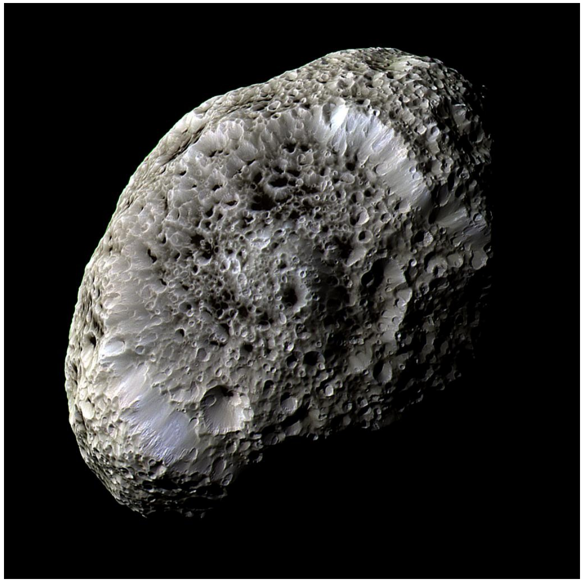


Image credit: NASA/JPL-Caltech/SSI

Low-velocity cratering in porous targets leads to high retention of projectile material.

Housen & Holsapple (2012). Cratering without ejecta. *Icarus* **219**, 297

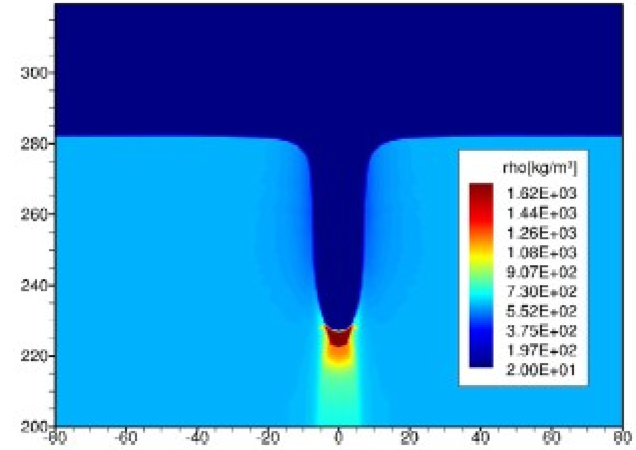


Image credit: de Niems *et al.* (2018, *Icarus* ***301****, 196*)

$$F = 1 - \exp\left(-N_{\text{coll}}\right)$$

Zone I, q=-3.0:

Target diameter [km]	Projectile diameter [km] (catastrophic)	Mean lifetime [Myr]	Fraction of population gone by 20 Myr	Diameter (upper limit) of *cratering* objects	Total accumulated mass (% of target)
128	70	210	9%	13 km	10.0
64	26	145	13%	4.8 km	5.0
32	9.7	97	19%	1.8 km	2.5
16	3.6	62	27%	670 m	1.2
8	1.4	38	40%	250 m	0.5
4	0.5	24	57%	94 m	0.3

Shape-changing collisions

Image credit: NASA/JPL/JHUAPL

50km Mathilde: 20-33km craters caused by 2-3km projectiles exemplify shape-changing impacts

Zone I, q=-3.0:

Target diameter [km]	Projectile diameter [km] (catastrophic)	Mean lifetime [Myr]	Fraction of population gone by 20 Myr	Diameter range of *shape-changing* objects [km]	Total accumulated mass (% of target)
128	70	210	9%	13–35	22.0
64	26	145	13%	4.8–13	10.4
32	9.7	97	19%	1.8–4.8	4.8
16	3.6	62	27%	0.67–2.2	2.2
8	1.4	38	40%	0.25 – 0.99	1.0
4	0.5	24	57%	0.09 – 0.41	0.4

Sub-catastrophic collisions

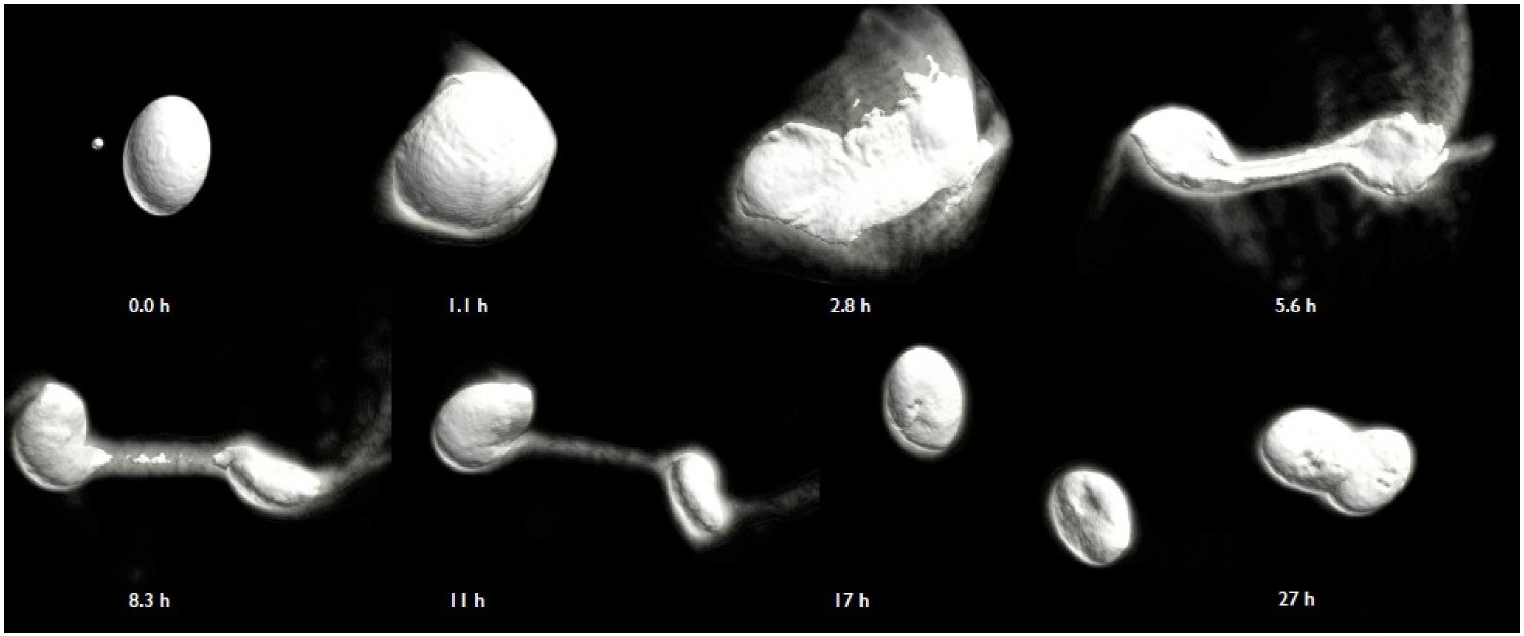


Image credit: Jutzi & Benz (2017, *A&A* **597**, A62)

Zone I, q=-3.0:

Target diameter [km]	Projectile diameter [km] (catastrophic)	Mean lifetime [Myr]	Fraction of population gone by 20 Myr	Diameter range of *subcatastrophic* objects [km]	Total accumulated mass (% of target)
128	70	210	9%	35–70	41.3
64	26	145	13%	13–26	18.2
32	9.7	97	19%	4.8–9.7	8.0
16	3.6	62	27%	2.2–3.6	3.5
8	1.4	38	40%	0.99 – 01.4	1.5
4	0.5	24	57%	0.41 – 0.50	0.7

Catastrophic collisions

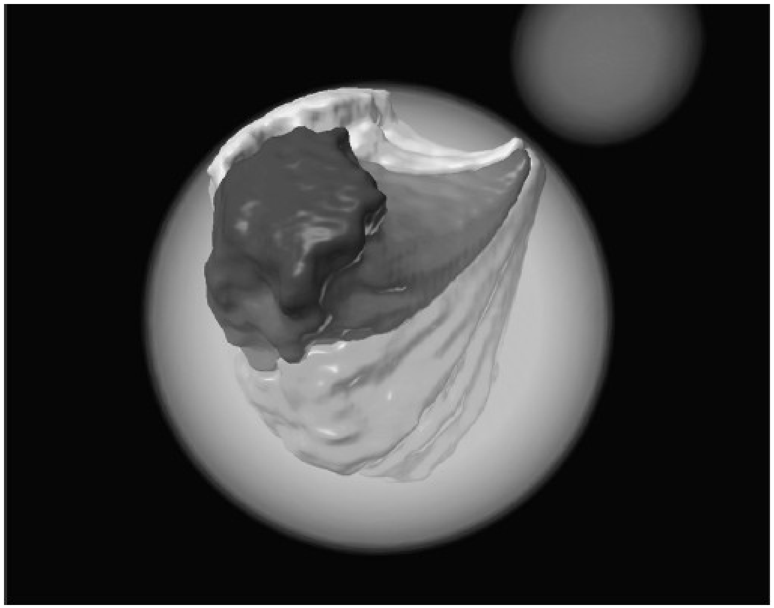


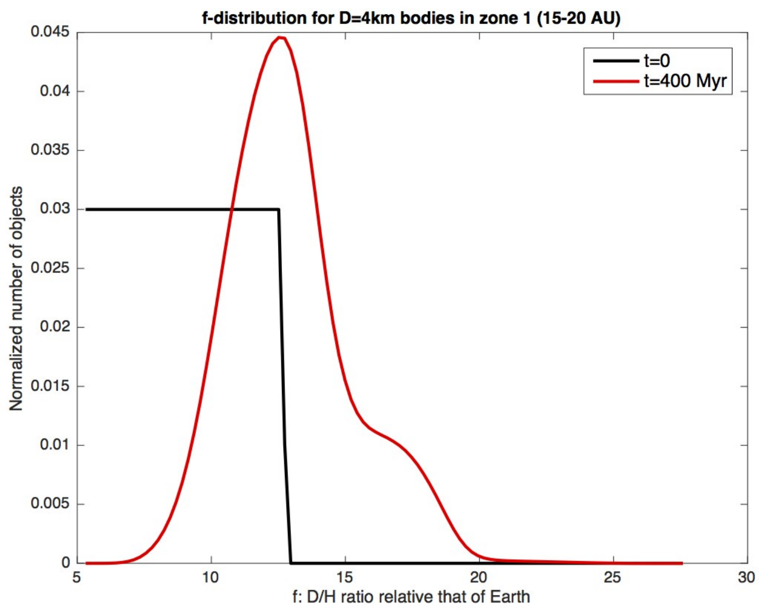
Image credit: Michel *et al.* (2015, *PSS* **107**, 24)

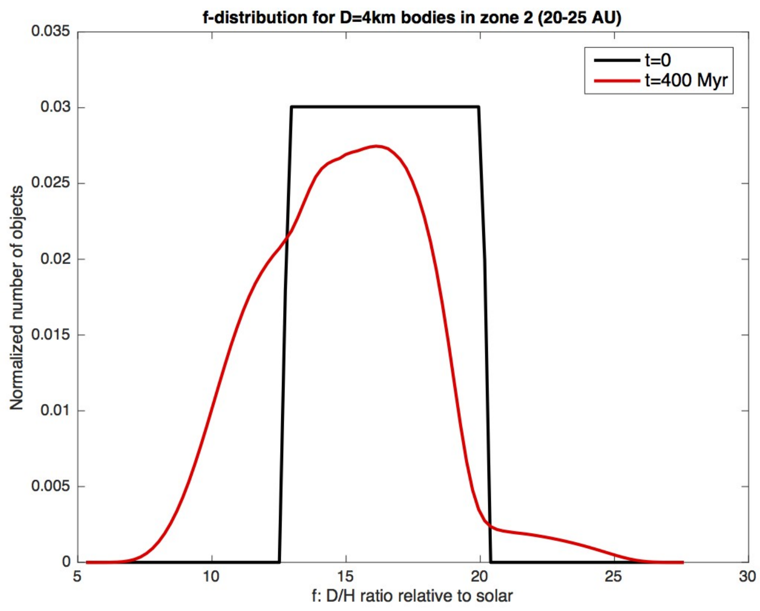
Target diameter [km]	Projectile diameter [km] (catastrophic)	Mean lifetime [Myr]	Fraction of population gone by 20 Myr	Total accumulated mass (% of target)
128	70	210	9%	16.1
64	26	145	13%	6.7
32	9.7	97	19%	2.8
16	3.6	62	27%	1.2
8	1.4	38	40%	0.5
4	0.5	24	57%	0.2

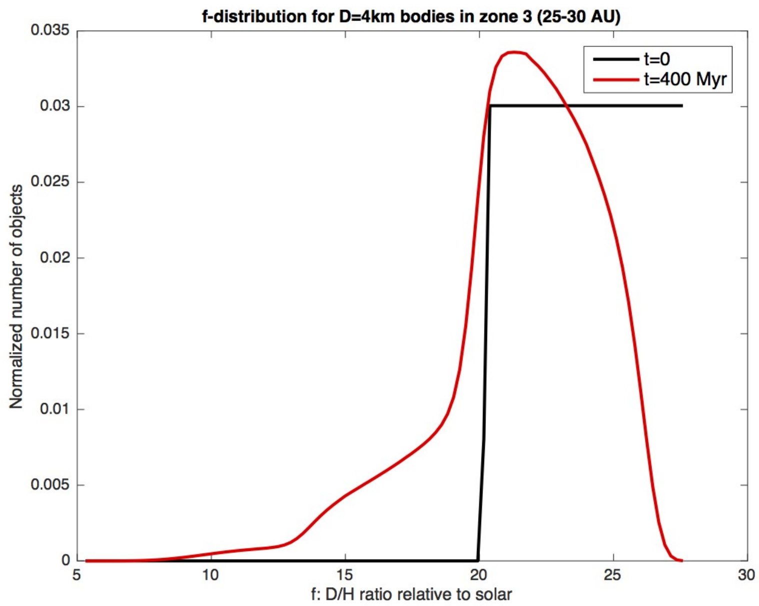
Numerical Code

- Mass at 15-30 AU: surface density prop. to r_h^{-1}
- Initial D/H (vs. solar): linear increase from f=5.2 (15 AU) to f=27.7 (30 AU)
  - Average and encapsulate the 9 known OCC/JFC; not get far below terrestrial f=7.4; 11% “Hartley 2’s” (f≤7.7) and 11% “67P’s” (f≥25.2)
- Small time steps (modeling 400 Myr)
  - For each size (D=4-140km, 1km resolution) and for each permutation of target/projectile zone:
    - Accumulation phase (cratering/shape changing/subcatastrophic collisions):
      - (N_{coll} depends greatly on considered collision type, time step and target/projectile zones)
      - N_{coll}>200: projectiles bring average f from their zone of origin
      - N_{coll}=1: all permutations of target and projectile f-values considered
      - 1<N_{coll}<200: weighted average of above f-distributions
      - N_{coll}<1: the N_{coll}=1 approach applied to appropriate subset of the population
    - Fragmentation phase
      - N_{cat} (number of disrupted bodies)>200: all permutations of target and projectile f-values considered
      - N_{cat} <200: random selection of target/projectile f-values
      - Fragments populate smaller size bins; change local f-distribution proportionally

Results (example)





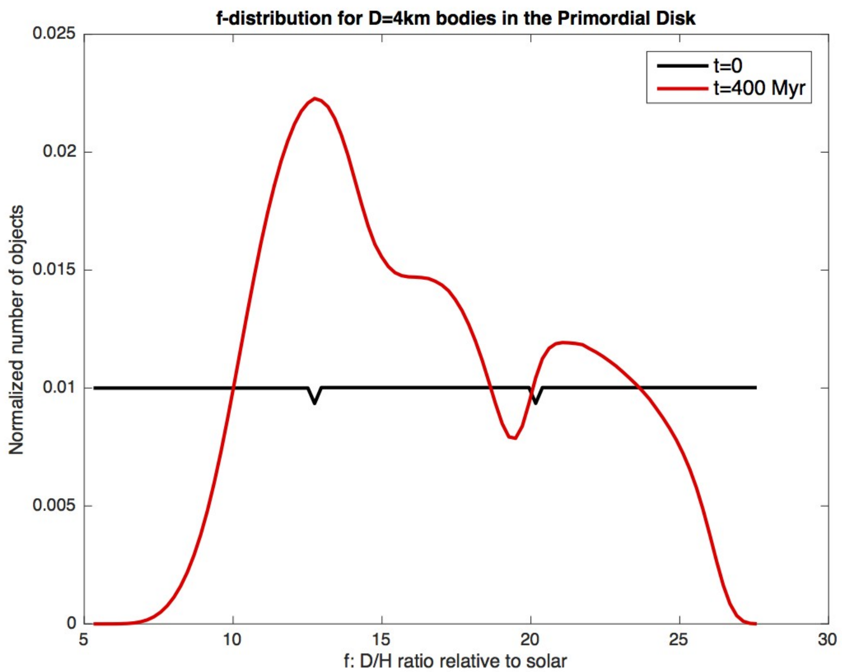


D=4km bodies, q=-3.0, one plot per zone

Local f-distributions *narrows* (majority of bodies) due to mixing of ice with different D/H ratios during collisions

Local f-distributions *shifts* and *broaden* (minority of bodies) due to exchange with other zones.

Consistency with observations



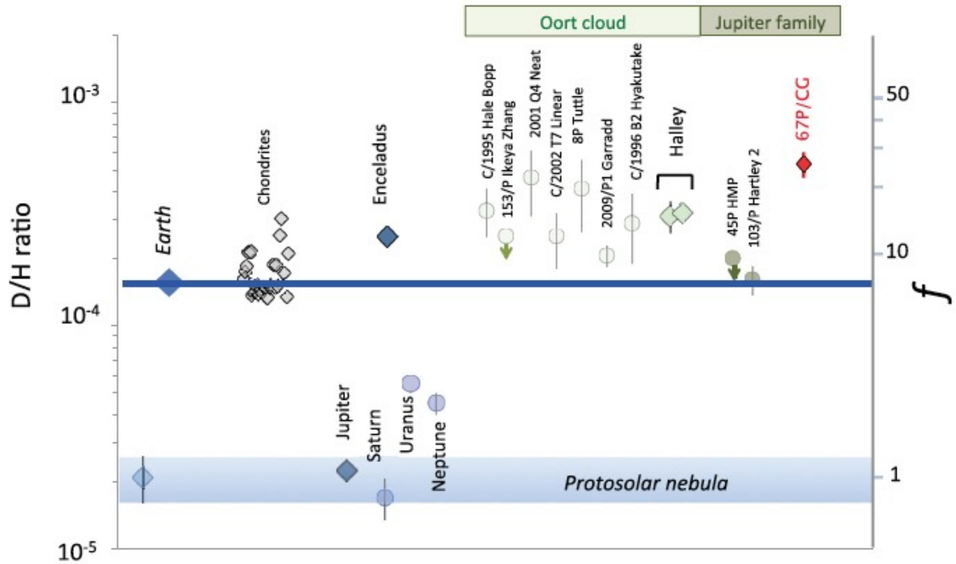


Image credit: Altwegg *et al.* 2015 (*Science* **347**, 1261952)

q=-3.0: entire population (zones merged)

t=0: 11% "103P" and 11% "67P"
t=400Myr: 0.06% "103P" and 2.1% "67P"

Drawing 9 objects randomly (10^4 times): probability of simultaneously having one 103P and one 67P:
t=0: 39%
t=200 Myr: 11%
t=400 Myr: 0.1%

q=-2.5:
t=200 Myr: 1%
t=400 Myr: 0.01%

q=-3.5:
t=200 Myr: 4%
t=400 Myr: 0%

Heating during collisions

- Motivation
- The thermal code NIMBUS
- First results

Motivation

Target diameter [km]	Projectile diameter [km] (catastrophic)	Time when 10% of targets disrupted [Myr]	Specific energy [J kg^{-1}]	Temperature increase [K] (assuming c=250 J kg^{-1} K^{-1})
128	102	62	$4.1 \cdot 10^4$	164
64	38	44	$1.7 \cdot 10^4$	69
32	14	30	$7.2 \cdot 10^3$	29
16	5.3	20	$3.0 \cdot 10^3$	12
8	2.0	12	$1.2 \cdot 10^3$	5
4	0.7	8	$5.2 \cdot 10^2$	2

q=-3.0, zone II

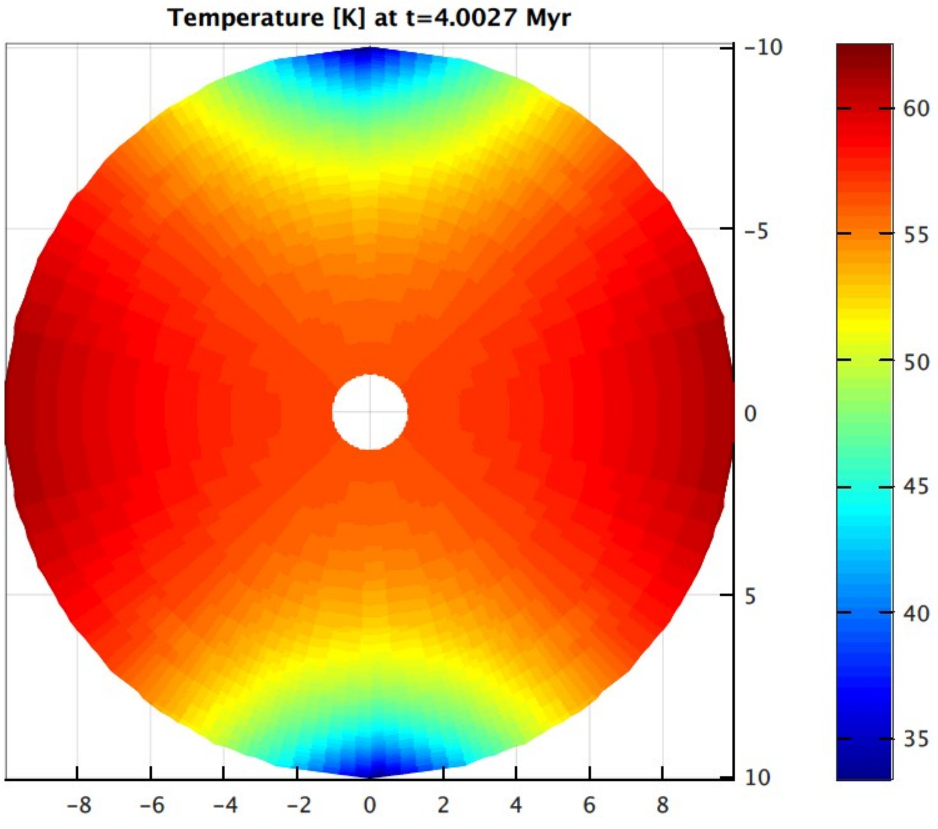
Catastrophic disruption of a D=5km parent with a largest fragment carrying 50% of the original mass (D=4km, 67P-like nucleus) results in negligible heating (also see, e.g., Jutzi & Benz, 2017, *A&A* **597**, A62)

But heating of parent bodies higher up in the collisional cascade chain brings body dangerously close to the CO_2 sublimation temperature (~80K) when added to the ~55K ambient temperature at the center of the Primordial Disk.

Condensed CO_2 the likely host of HCN, much of the CO, N_2, Ar, and CH_4; all these species at risk.

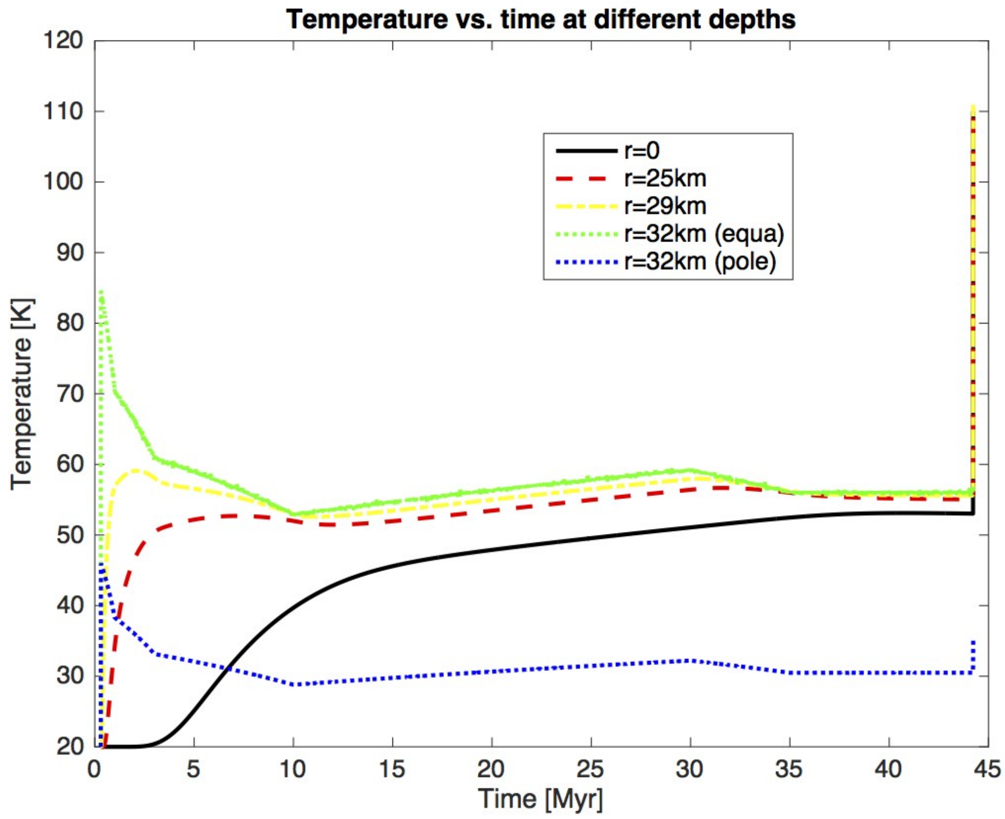
NIMBUS

Numerical Icy Minor Body nUmerical Simulator



- Solar heating (time-dependent luminosity for 1 solar-mass protostar)
- Thermal reradiation surface cooling
- 2D heat conduction (radial, latitudinal), function of temperature and porosity
- Temperature-dependent specific heat capacities (80% forsterite, 20% water ice)
- Catastrophic impacts producing daughters with 50% mass of parent
- Half the energy of the projectile, minus kinetic energy losses to other fragments (Benavidez & Camp Bagatin 2009, *PSS* **57**, 201) heat parent homogeneously in a short pulse event
- Fed as initial temperature to new smaller body that cools until the next hit

Example



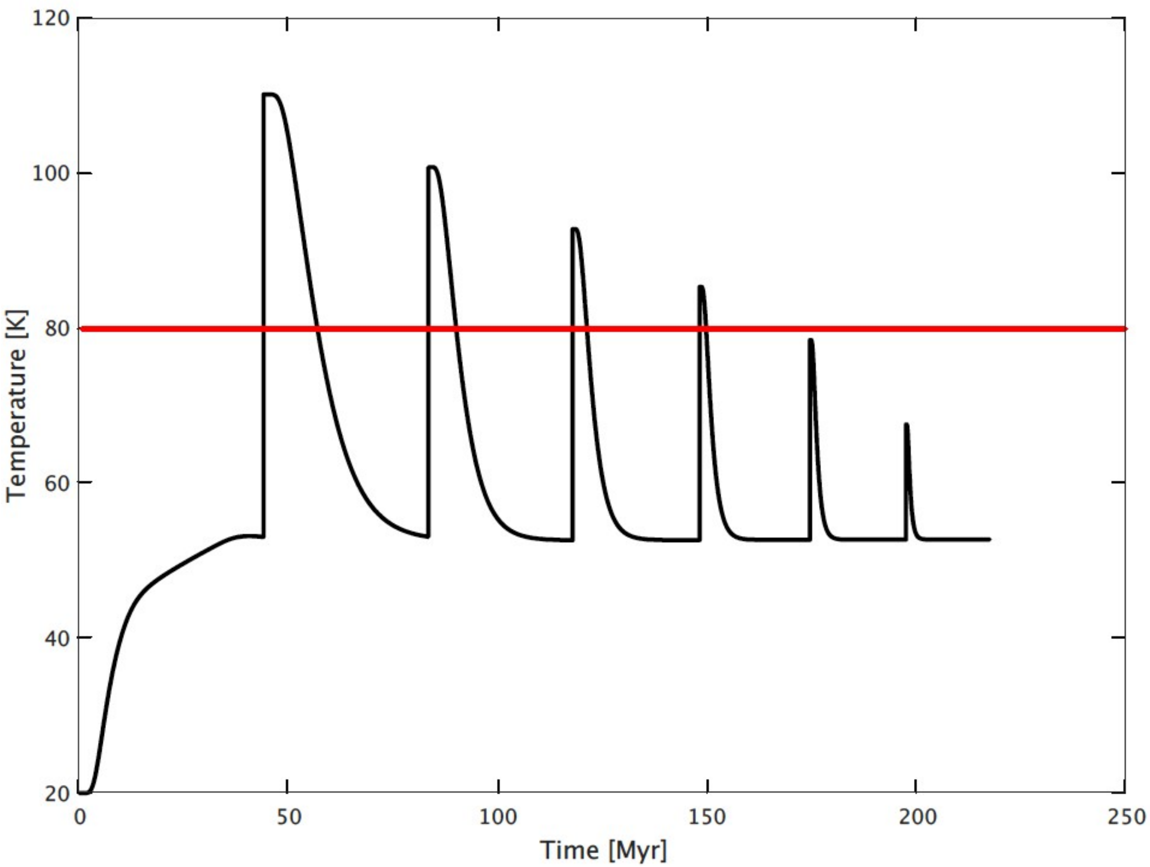
D=64km

T=20K at 0.3Myr after CAI, adjusting to protostar heating to T=53K at the core.

Impacted at t=44.2 Myr, a D=50.8km daugther formed with T=110K

This is far above the sublimation temperature of CO_2 and its trapped species

Example



Consecutive hits elevates temperature above 80K at disruption of D>=25km bodies

Conclusions

- D/H homogenization appear efficient: <0.1% probability of finding a Hartley 2 (D/H=7.7 times solar) and a 67P (D/H=25.2 times solar) among 9 objects

- Collisional heating during disruption of D≥25km bodies likely leads to global CO_2 loss

- Comets like Rosetta's 67P are not likely to have been formed as part of a collisional cascade. They are most likely pristine